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LA-UR-17-30708
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Title: 5 years of research of Differential Die-Away (DDA) Instrument within the Next Generation Safeguards Initiative

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Intended for: presentation to sponsor

Issued: 2017-11-22

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5 years of research of Differential Die-Away (DDA) Instrument within the Next Generation Safeguards Initiative

What have we learnt?

Vlad Henzl

NEN-1

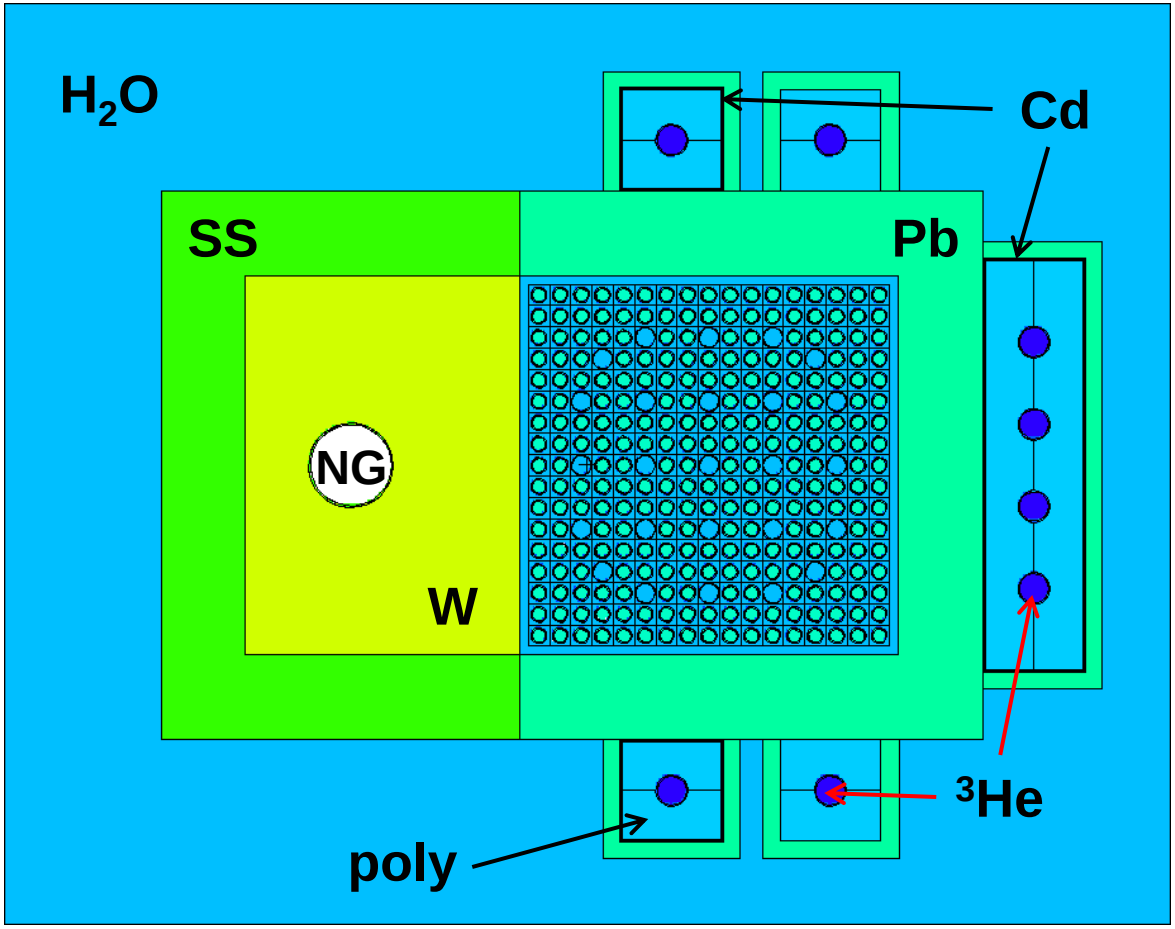
Overview (DDA@NGSI)

- **2009 – 14 NDA techniques started** *(… not all made it)*
- **2011 – NGSI Project merit review - DDA almost abandoned**
- **2014 – one of the most comprehensive and promising techniques**
- ***2015*+ – design/build of prototype for CLAB, Sweden**

- **15+ people contributed (***Pauline Blanc, Stephen Croft, Kiwan Chung, Noah Fisher, Alison Goodsell, Vlad Henzl, Taehoon Lee, Henrik Liljenfeld, Niklas Lundquist, Tomas Martinik, Howard Menlove, Martyn Swinhoe,Steve Tobin, Holly Trellue, Rob Weldon, …***)**

- **tested against simulations of 1000+ SFA's**
  (SFL-1, 2a, 2c, 2e, 3, 4, 5, 6)

Original DDA(+DN) Instrument Design

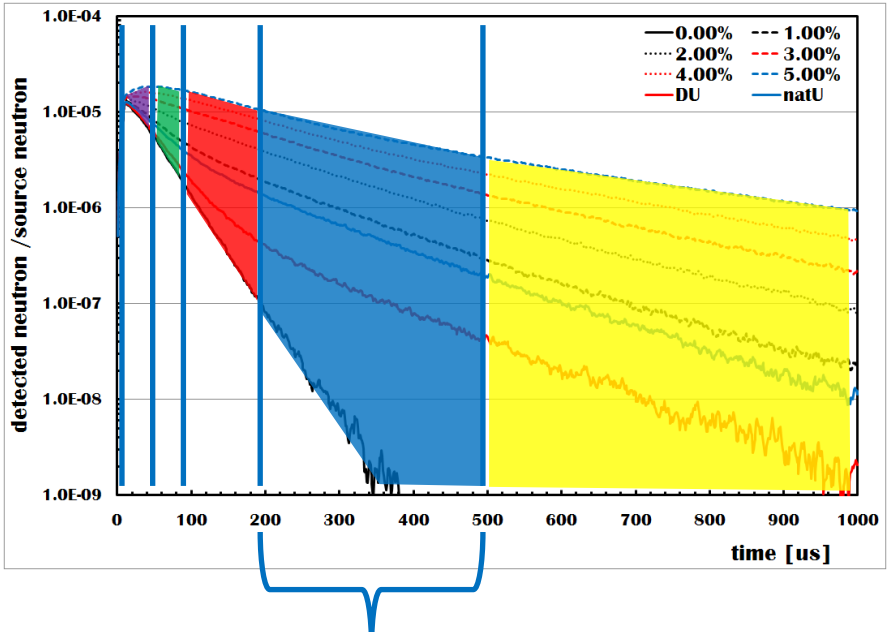


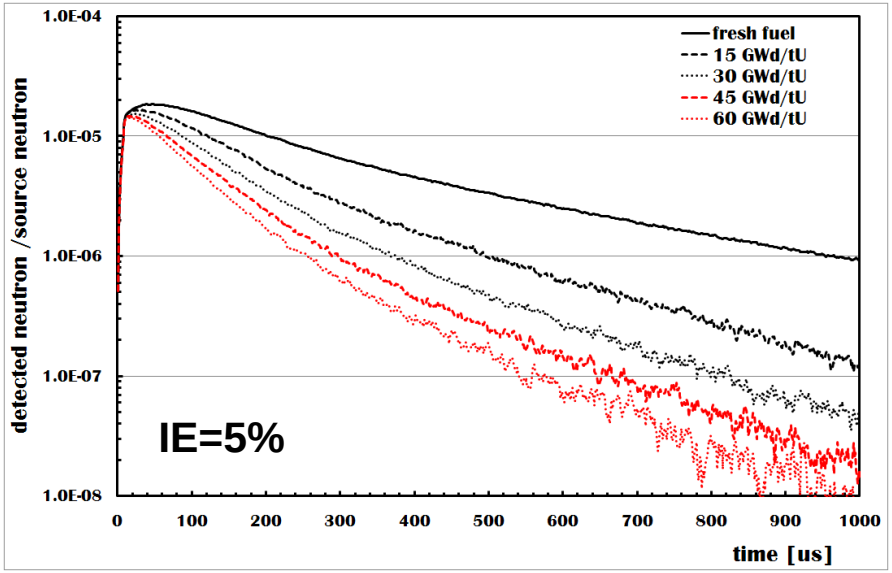
Design by P. Blanc & H. Menlove

- **DDA+DN Instrument Design**
  - ***Stainless steel*** (SS) as a reflector
  - ***6x ^{3}He w/ Cd*** used for DDA and DN, but efficiency for DN ~50% smaller due to Cd
  - ***2x ^{3}He w/o Cd*** to improve efficiency of DN instrument (i.e. DN only)

DDA response phenomenology (*fresh fuel vs. spent fuel*)

- **Fresh fuel => DDA response increases (die-away time is longer) with increasing fissile content**
- **Spent fuel => DDA response decreases (die-away time is shorter) with higher burn-up (i.e. more neutron absorbers present)**





DDA signal = integral of counts in a given time domain (without the contribution of burst neutrons)

2011 External Review of DDA

Charlton & Humphrey

JNMM 40(3), 18-23(2012)

	DDA
General Characteristics	
Time Required for Development	Short
Portable	N
Cost (High, Med, Low)[g]	H
Practical Implementation when Fixed in a Facility	Y
Hardware Maturity	High
Quantification Ability for Assemblies for:	
Elemental Pu	N
^{239}Pu	N
^{235}U	N
^{241}Pu	N
^{240}Pu	N
^{239}Pueff	Y
Fission product absorbers	N
Other actinide absorbers	N
^{239}Pueff Quantification Penetrability (# rows)	9
Burnup	N
Initial Enrichment	N
Cooling Time	N
Pin Diversion Sensitivity[i] (High, Med, Low) in:	
Outer Region (rows 1-2)	M
Middle Region (rows 3-5)	M
Center Region (rows 6-9)	M
Independence of (for Fissile Mass Quantification):	
Burnup	N
Initial Enrichment	N
Cooling Time	N
Priority for More Work	2

2014 Status of DDA

Internal Review

	DDA
General Characteristics	
Time Required for Development	Short
Portable	Y
Cost (High, Med, Low)[g]	H
Practical Implementation when Fixed in a Facility	Y
Hardware Maturity	High
Quantification Ability for Assemblies for:	
Elemental Pu	Y
^{239}Pu	N
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^{241}Pu	N
^{240}Pu	N
^{239}Pueff	Y
Fission product absorbers	Y
Other actinide absorbers	Y
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Burnup	Y
Initial Enrichment	Y
Cooling Time	Y
Pin Diversion Sensitivity[i] (High, Med, Low) in:	
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Center Region (rows 6-9)	M
Independence of (for Fissile Mass Quantification):	
Burnup	Y
Initial Enrichment	Y
Cooling Time	Y
Priority for More Work	2

2011 External Review of DDA

Charlton & Humphrey

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Independence of (for Fissile Mass Quantification):		
	Burnup	N
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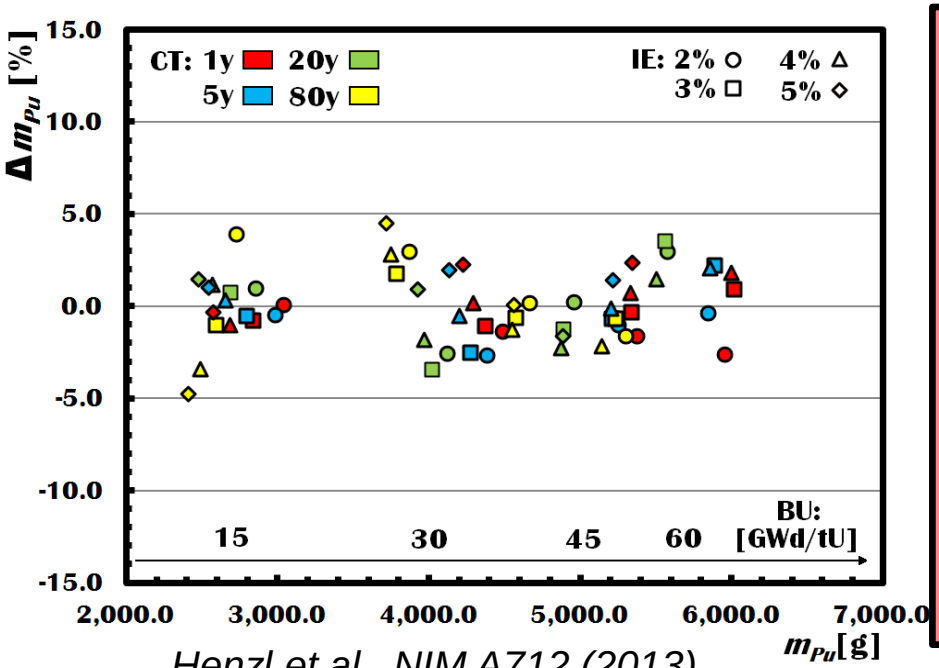
Priority for More Work		2

2014 Status of DDA

- Any instrument that measures multiplication and passive neutrons can determine tot m_{Pu}

$$m_{Pu} = a(CT)\frac{M+2c}{M+c}\left[\left(\frac{M}{M+2c}\right)NE\right]^{b(CT)}$$



Henzl et al., NIM A712 (2013)

BUT : CT needs to be constrained

2011 External Review of DDA

Charlton & Humphrey

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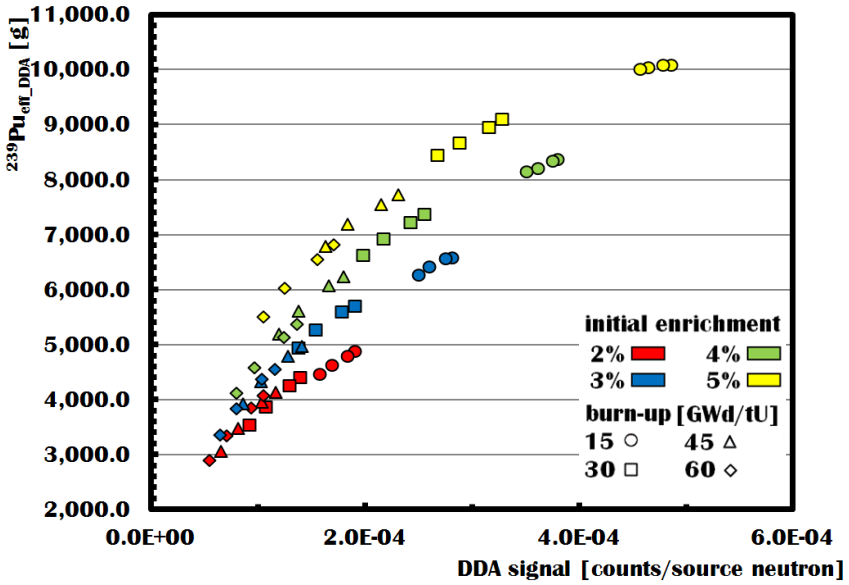
2014 Status of DDA

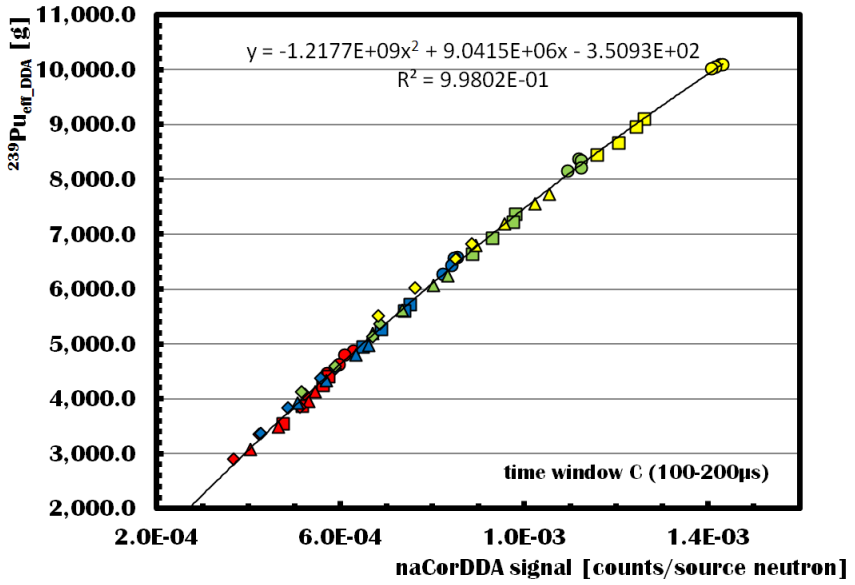
$$^{239}Pu_{eff} = c_1 m(^{235}U) + m(^{239}Pu) + c_2 m(241Pu)$$

Measurement of $^{239}Pu_{eff\_DDA}$ (in time domain 100-200μs)

UNCORRECTED



CORRECTED



- let's correct DDA signal by the die-away time

$$\boldsymbol{CorDDA} = \boldsymbol{DDA}(SFA,t) \cdot \tau^{\varepsilon(t)}$$

ε = -2.03
σ = 1.74%

2011 External Review of DDA

Charlton & Humphrey

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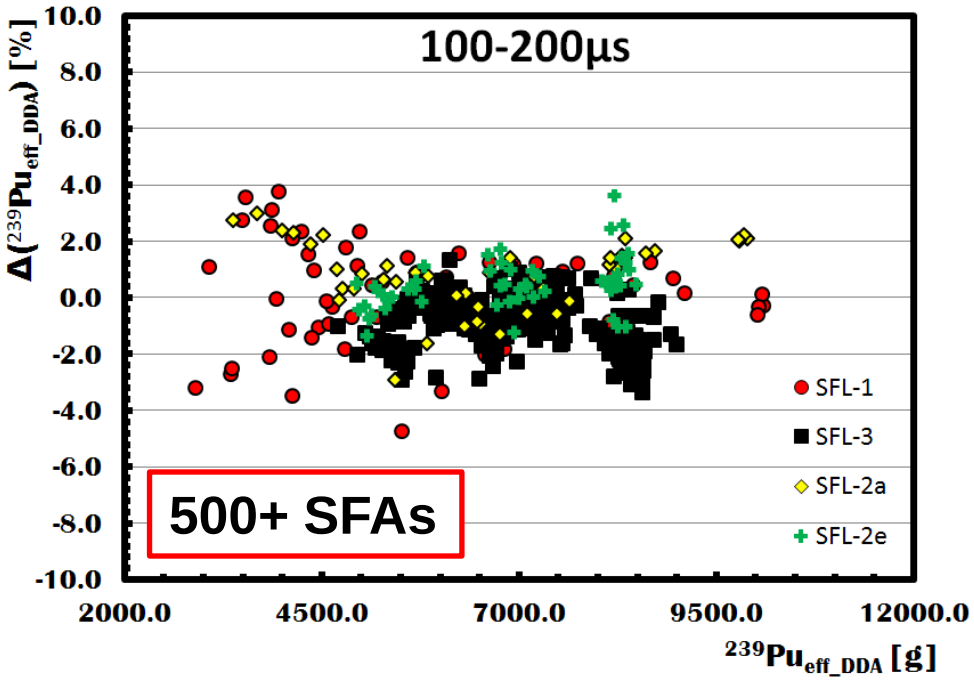
2014 Status of DDA

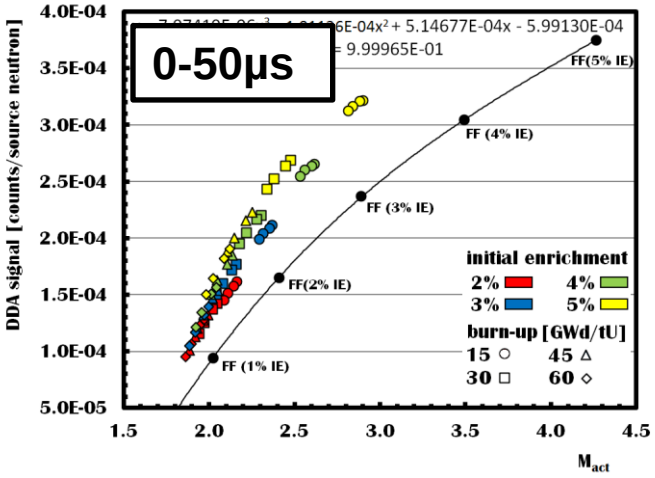
$$^{239}Pu_{eff} = c_1 m(^{235}U) + m(^{239}Pu) + c_2 m(241Pu)$$

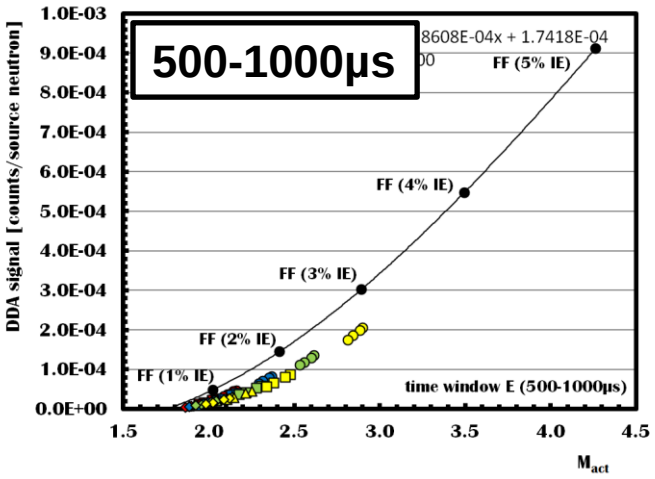
- DDA signal needs to be corrected by die-away time
- ***$^{239}Pu_{eff}$ independent of IE, BU, CT***



…what is the meaning of die-away time ?

DDA response & evaluation of neutron absorbers



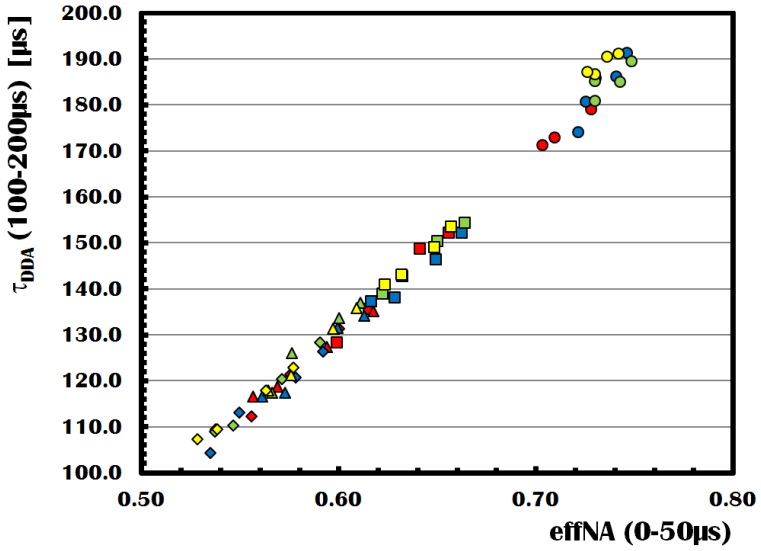


- "*effective neutron absorber coefficient*":

$$\boldsymbol{effNA = DDA^{FF} / DDA^{SFA}}$$

=> Ratio of DDA signal for fresh fuel (FF) and spent fuel (SFA) for given ***M*** and given time domain

=> also reflected by die-away time (!!!)



2011 External Review of DDA

Charlton & Humphrey

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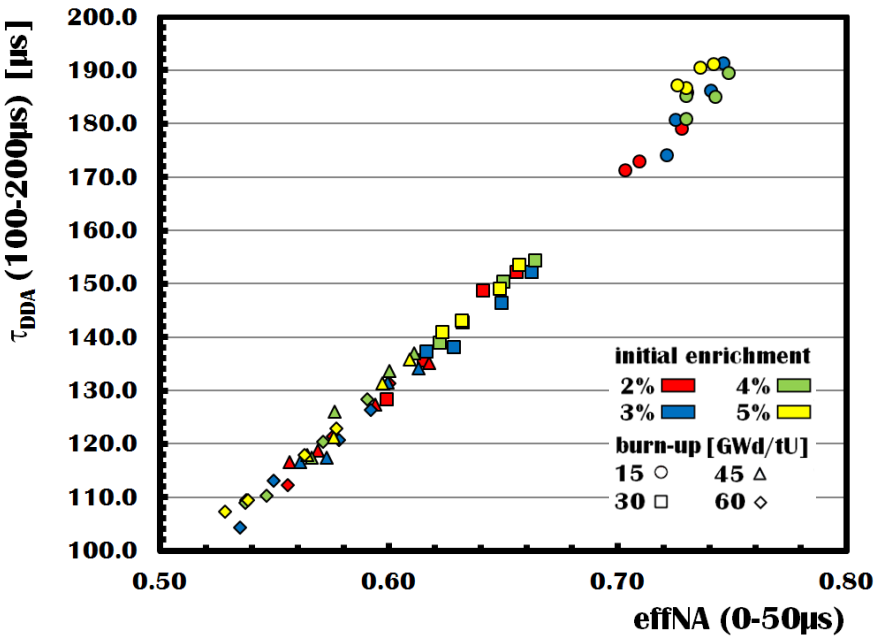
Priority for More Work	2

2014 Status of DDA

$$effNA = DDA^{FF} / DDA^{SFA}$$

- ***effNA*** – effective neutron absorbers
- ***Die-away time is a measure of neutron absorbers in the SFA***



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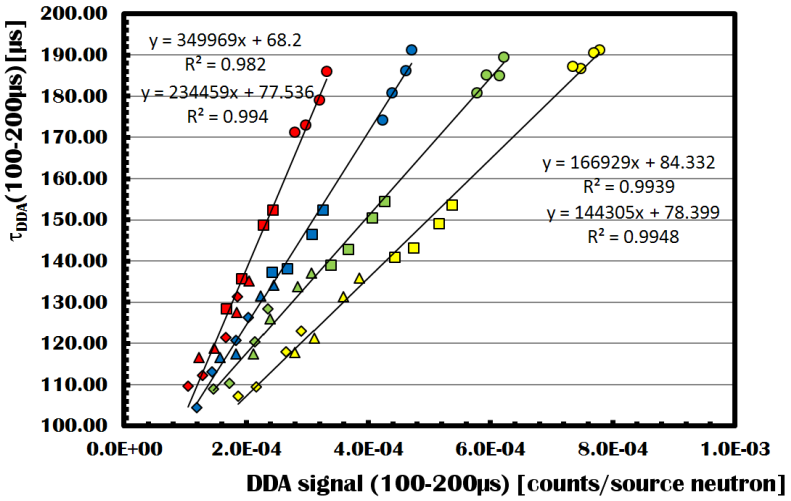
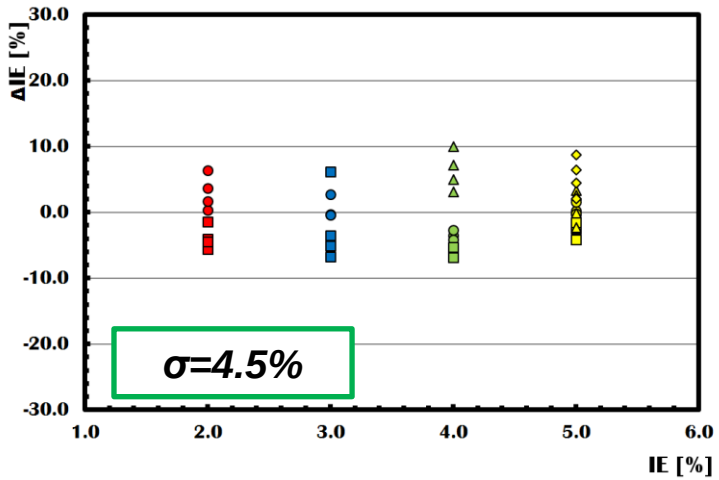


$$\tau_{DDA} = a(IE)\cdot \mathbf{DDA} + b(IE)$$



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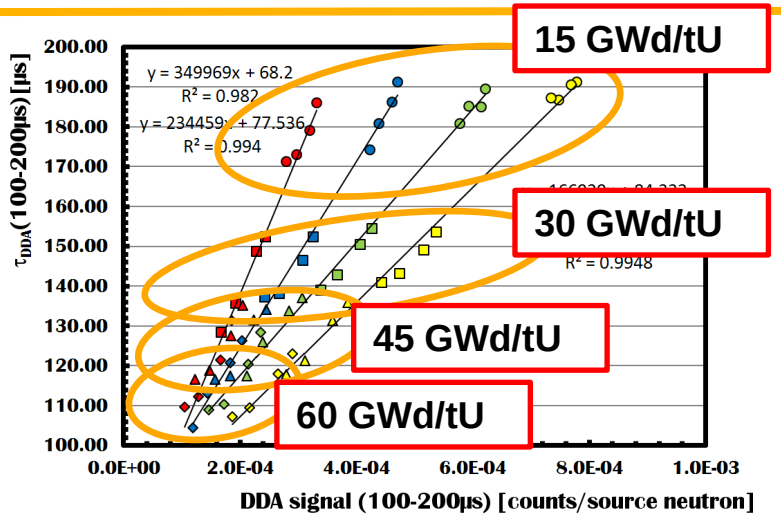
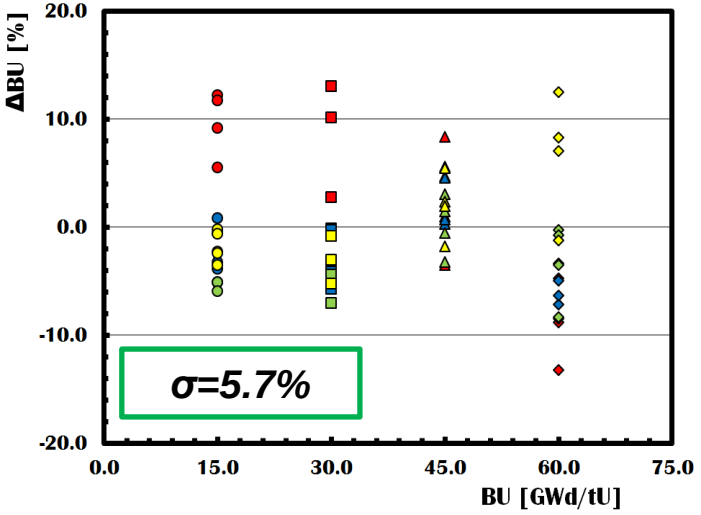


BUT : CT needs to be known



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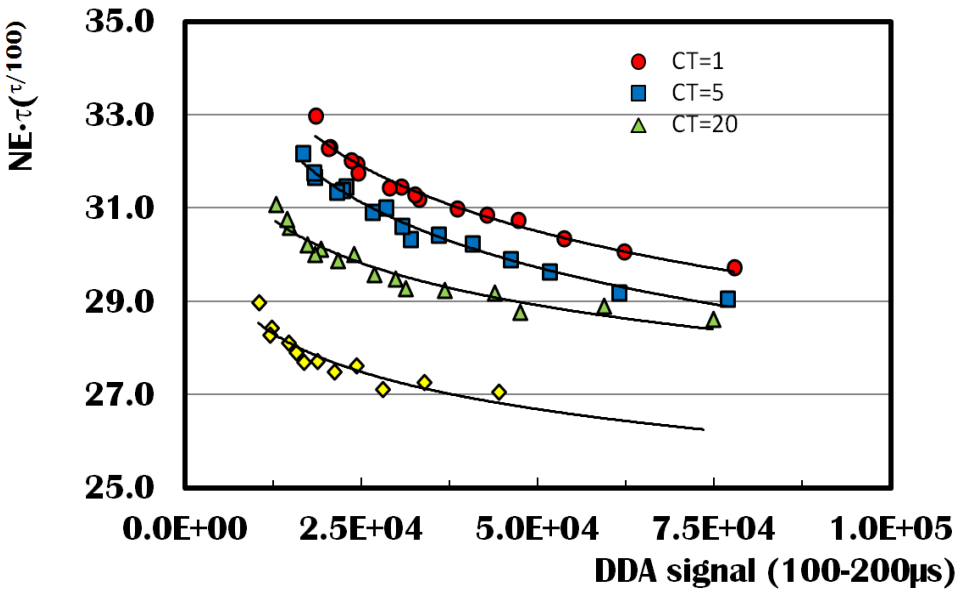
2014 Status of DDA

Unfinished work

=> first results promising



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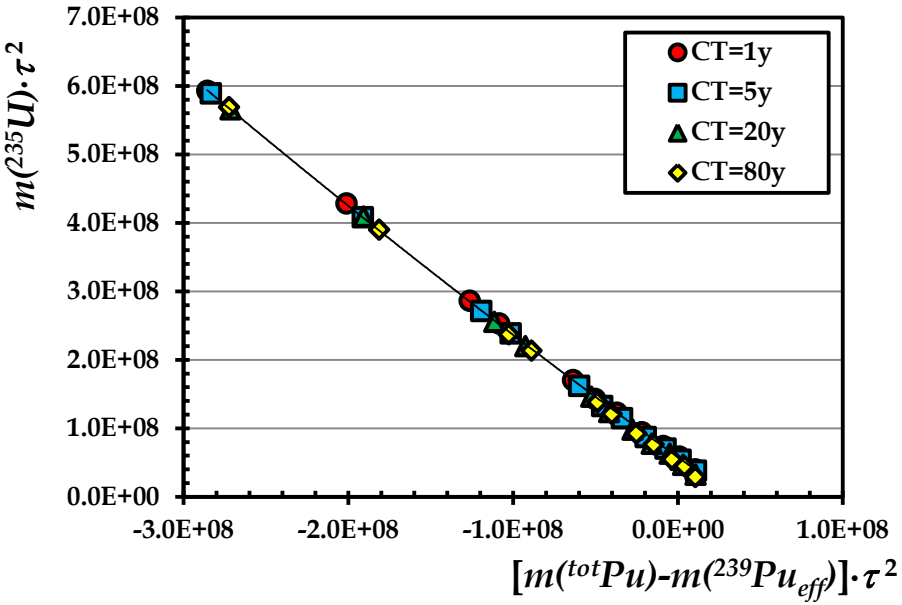
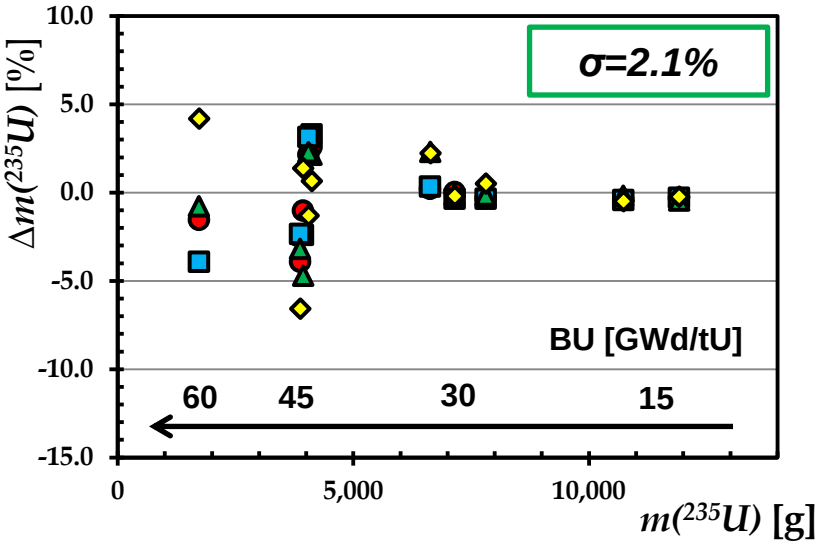
October 2014:





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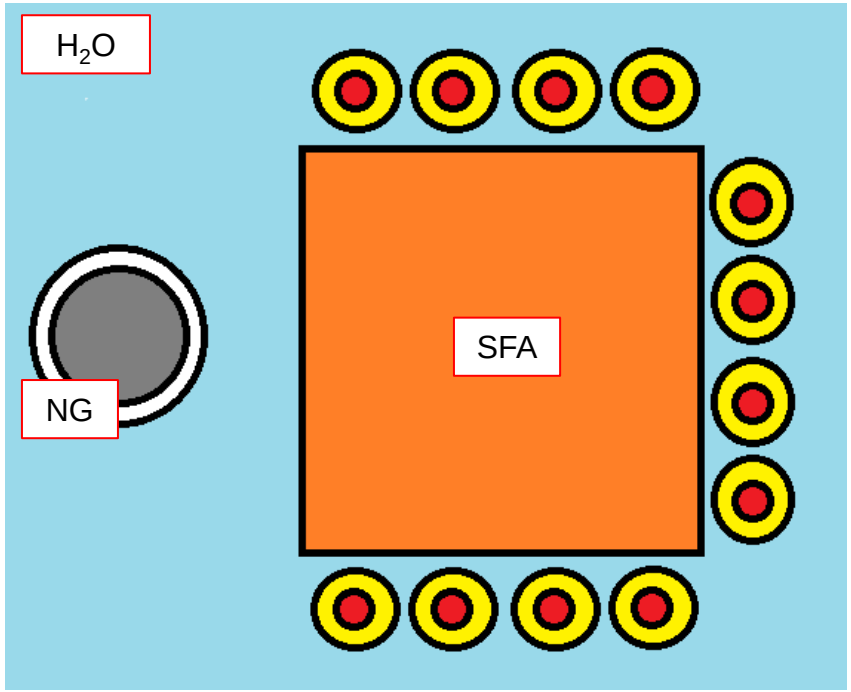
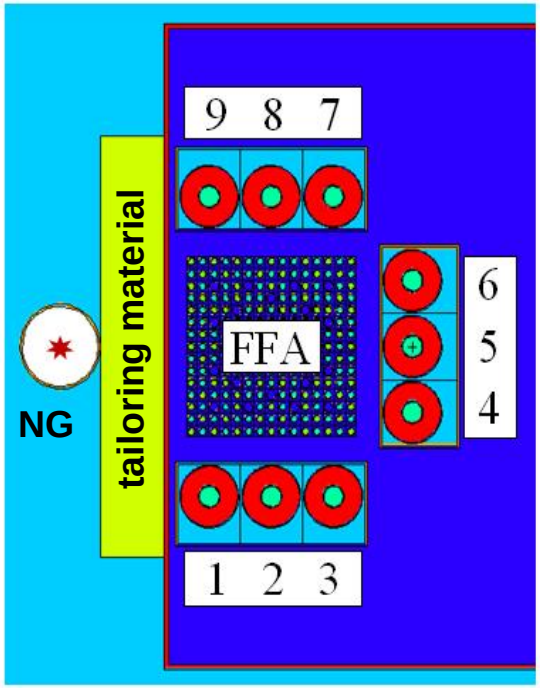
October 2014:

- With fission chambers no Pb shielding needed
- DDA works without tailoring material too

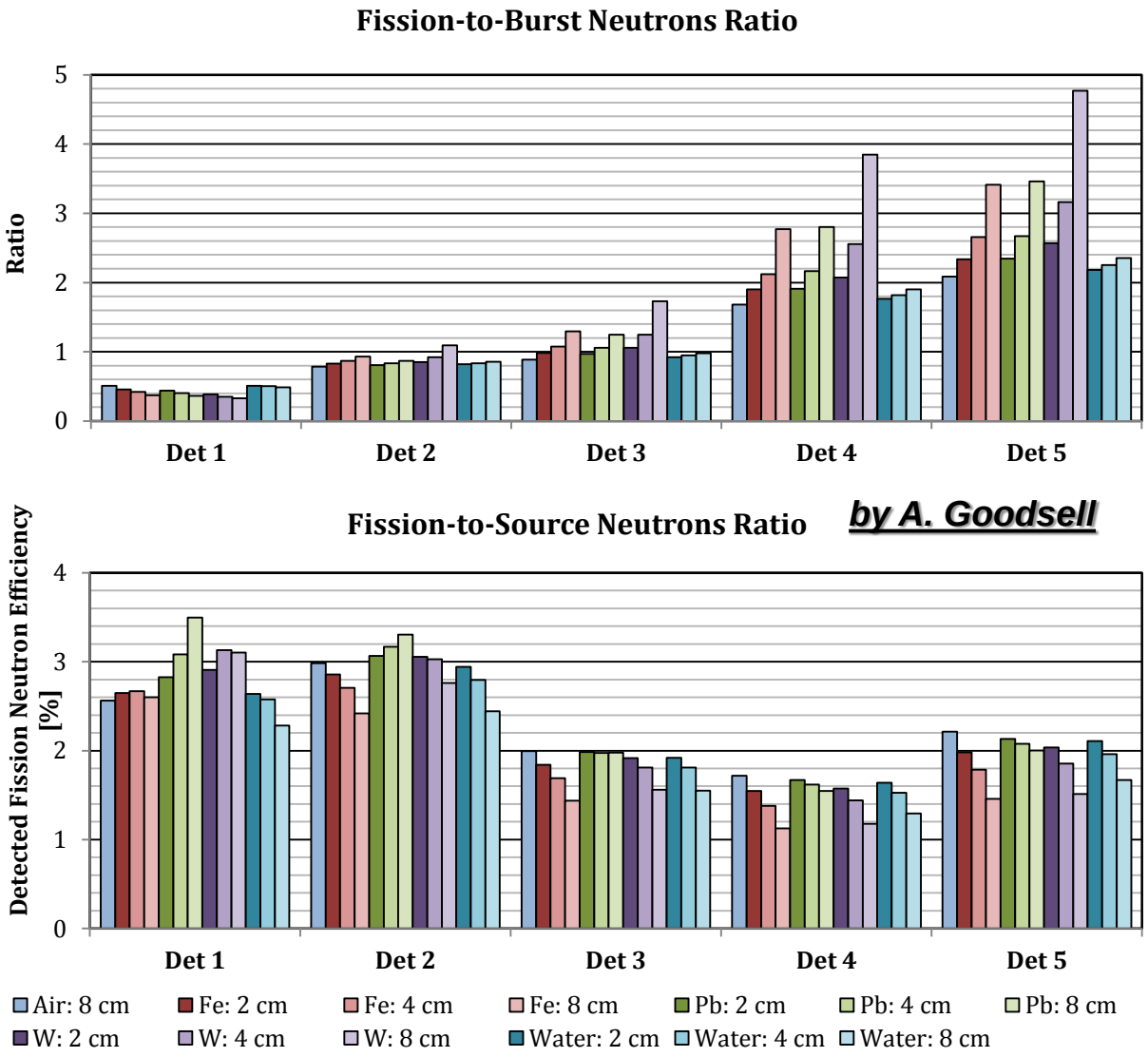


by Niklas Lundkvist

How to tailor NG neutrons ?

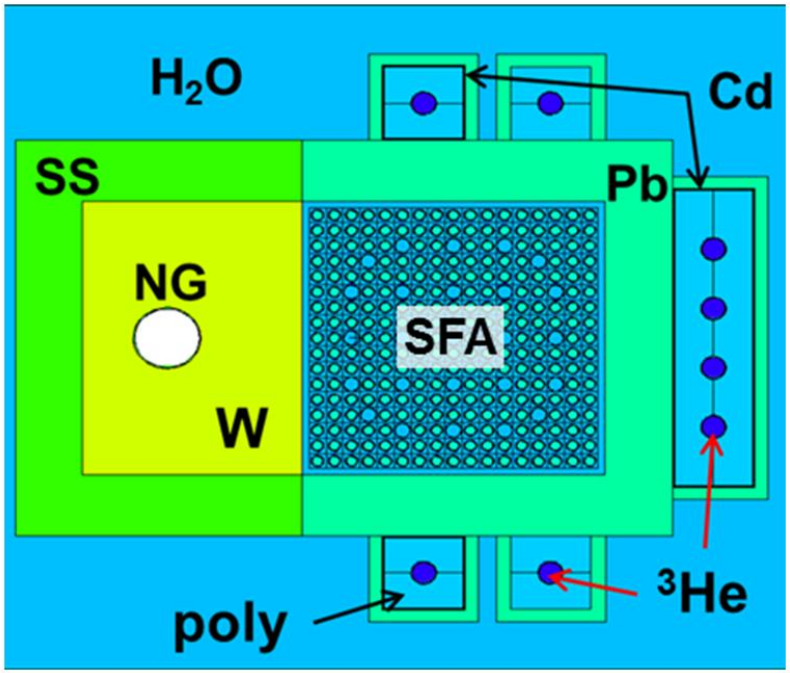


- Choice of tailoring material is ***not*** very significant



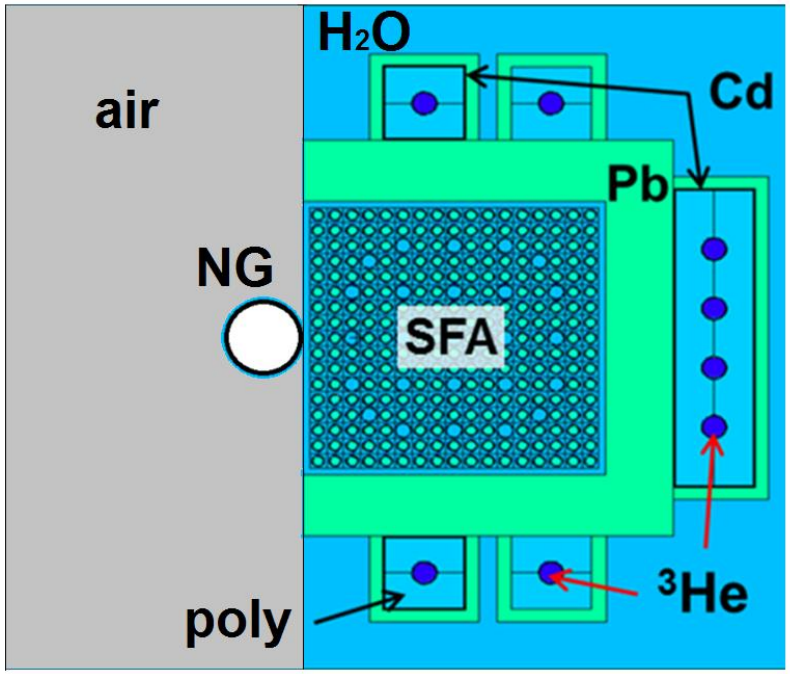
To tailor or not to tailor ?

"***base***" design



- Neutrons entering SFA have energy **< 1.0 MeV**
- Fast fission on ^{238}U ***minimized***

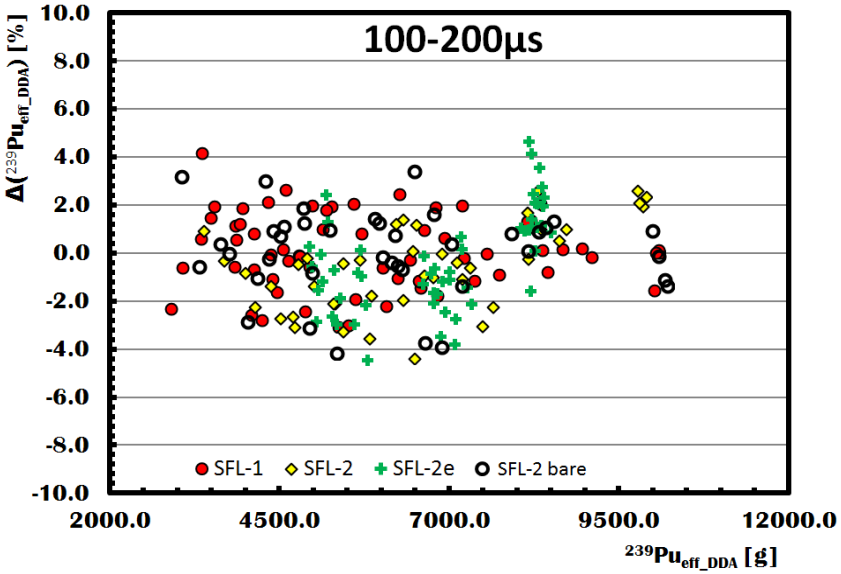
"***bare***" design



- Neutrons entering SFA have energy of **14.1 MeV**
- Fast fission on ^{238}U ***maximized***

To tailor or not to tailor ?

- Any DDA design is evaluated on its ability to determine $^{239}Pu_{eff}$



- "Bare" design performs just as well as other designs with tailoring material

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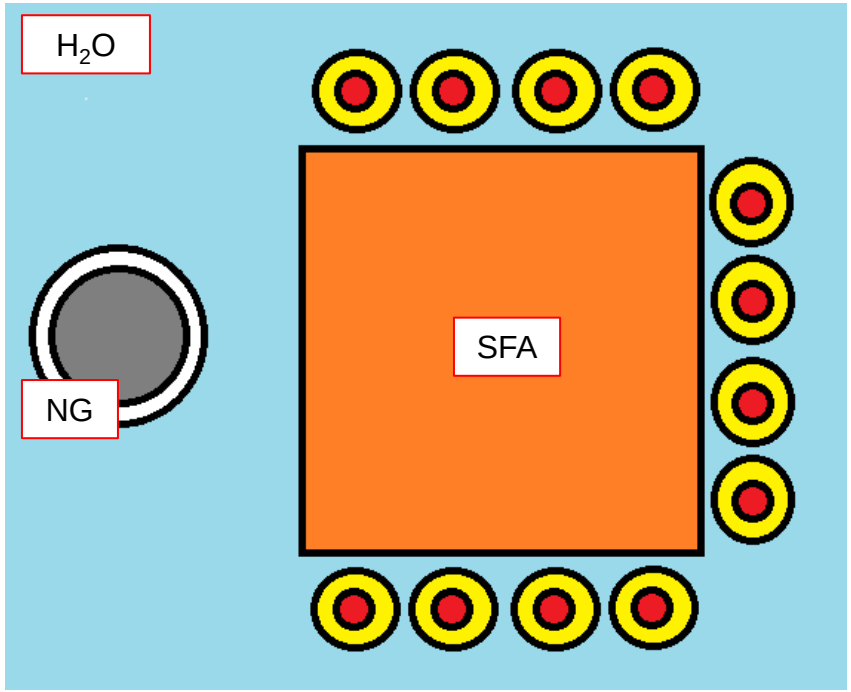
Pin Diversion Sensitivity[i] (High, Med, Low) in:	
Outer Region (rows 1-2)	M
Middle Region (rows 3-5)	M
Center Region (rows 6-9)	M
Independence of (for Fissile Mass Quantification):	
Burnup	N
Initial Enrichment	N
Cooling Time	N
Priority for More Work	2

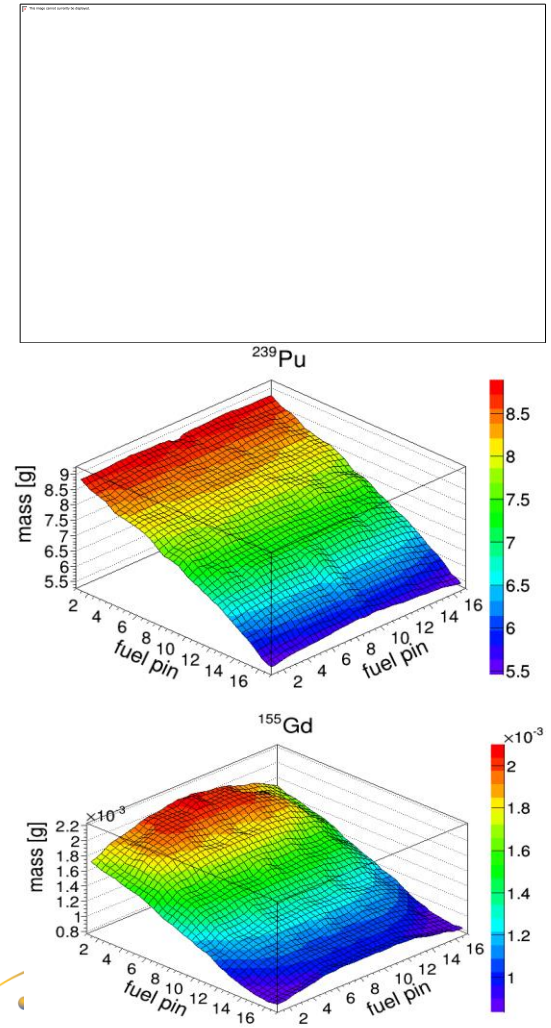
October 2014:

- With fission chambers no Pb shielding needed
- DDA works without tailoring material too

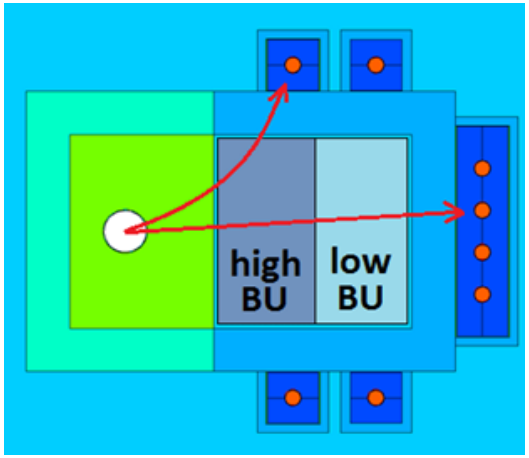


by Niklas Lundkvist

Role of individual detectors



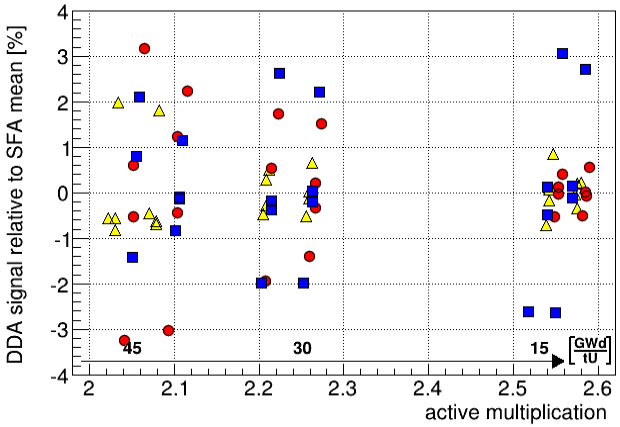
- ***SFL2e*** – highly asymmetrically burned SFA's
- BU asymmetry develops when SFA burned on the edge of the reactor core
- Most of SFA's in real world likely have asymmetric BU
- Simulated assay of SFA from 4 sides



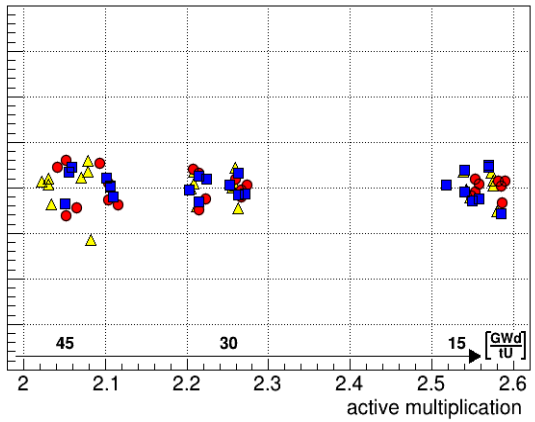
Role of individual detectors

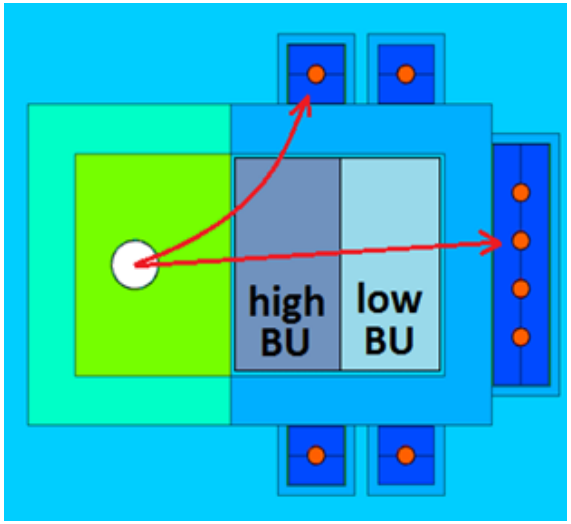
- DDA response sensitive to orientation of SFA only for ***FRONT*** detectors
- ***BACK*** detectors ***NOT*** sensitive to SFA orientation

front detectors



back detectors





by Tomas Martinik

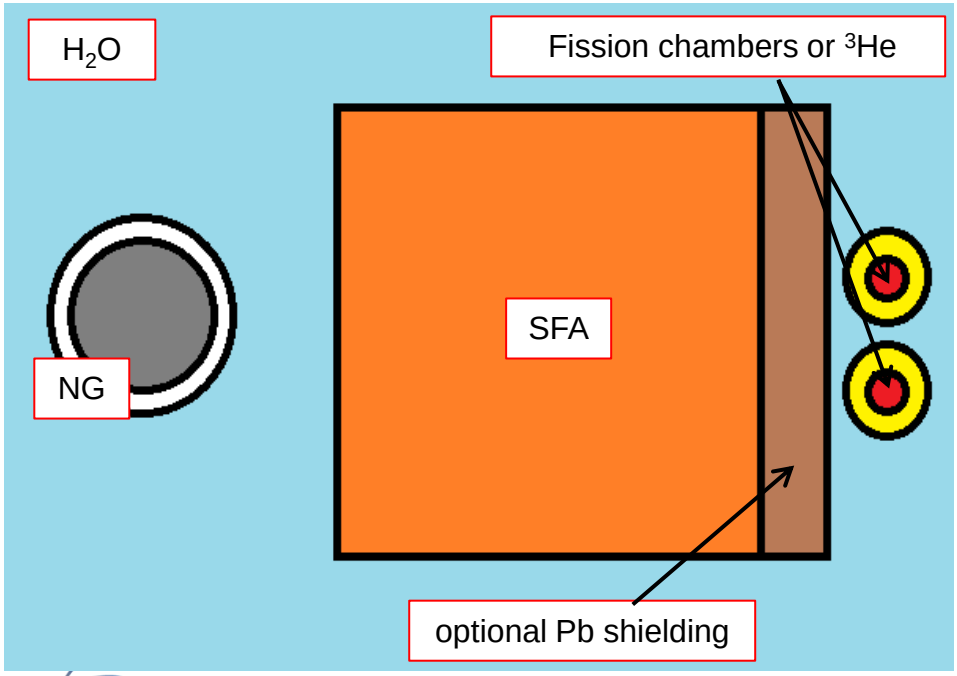
SFA's with 4% IE, 15-45 GWd/tU BU, CT=5, 20y
(*3 different shuffling scenarios*)

FRONT detectors = local assay
BACK detectors = global assay

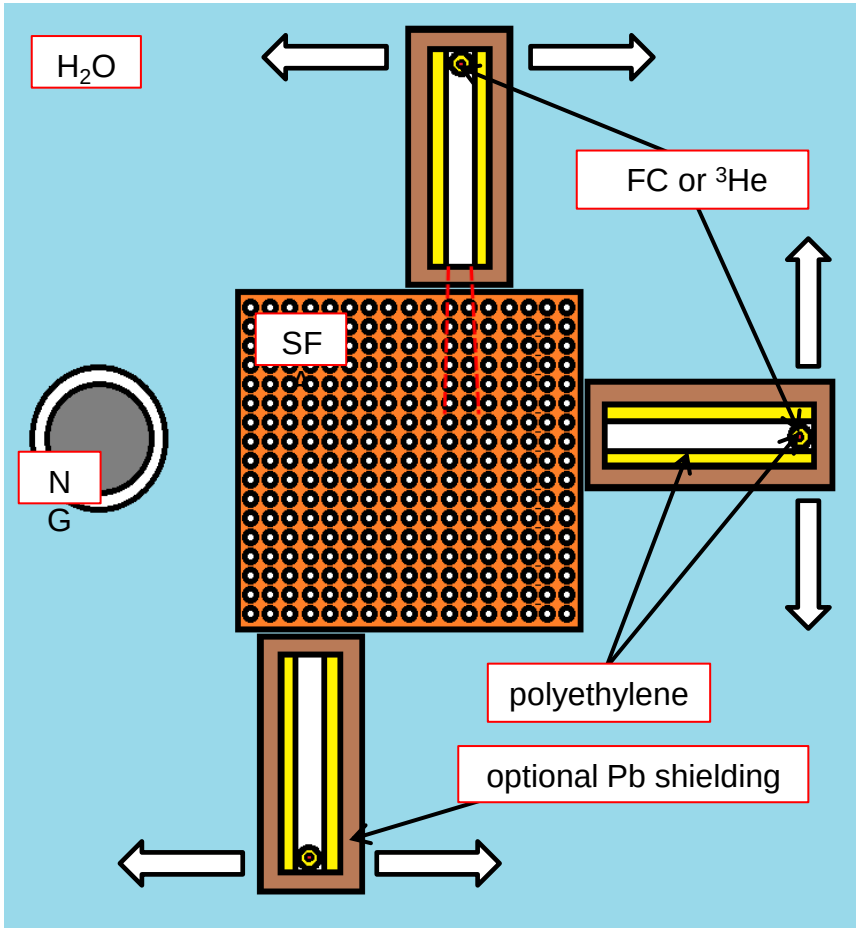
Novel DDA designs

- Understanding of DDA opens new possibilities

Minimalist DDA

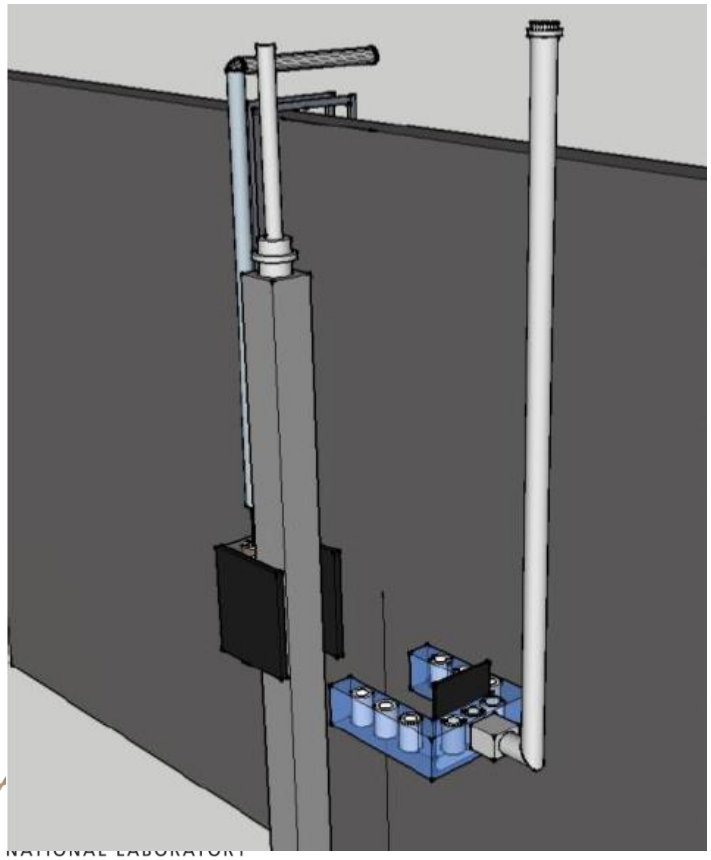


Defectoscope DDA



DDA Fork detector

- Culmination of NA-22 funded project of experimental verification of DDA "physics" predicted by NA-241 funded simulations



- 2 parts of the instrument
  - NG with Pb shielding
  - 3He/FC detectors & more in a Fork-like configuration
- Portable system for spent fuel pond measurements
- Operated by 1-2 inspectors by the side of the pool
- Full benefits of traditional DDA

Summary

2011

	DDA
General Characteristics	
Time Required for Development	Short
Portable	N
Cost (High, Med, Low)[g]	H
Practical Implementation when Fixed in a Facility	Y
Hardware Maturity	High
Quantification Ability for Assemblies for:	
Elemental Pu	N
^{239}Pu	N
^{235}U	N
^{241}Pu	N
^{240}Pu	N
^{239}Pueff	Y
Fission product absorbers	N
Other actinide absorbers	N
^{239}Pueff Quantification Penetrability (# rows)	9
Burnup	N
Initial Enrichment	N
Cooling Time	N
Pin Diversion Sensitivity[i] (High, Med, Low) in:	
Outer Region (rows 1-2)	M
Middle Region (rows 3-5)	M
Center Region (rows 6-9)	M
Independence of (for Fissile Mass Quantification):	
Burnup	N
Initial Enrichment	N
Cooling Time	N
Priority for More Work	2

2014

	DDA
General Characteristics	
Time Required for Development	Short
Portable	Y
Cost (High, Med, Low)[g]	H
Practical Implementation when Fixed in a Facility	Y
Hardware Maturity	High
Quantification Ability for Assemblies for:	
Elemental Pu	Y
^{239}Pu	N
^{235}U	Y
^{241}Pu	N
^{240}Pu	N
^{239}Pueff	Y
Fission product absorbers	Y
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^{239}Pueff Quantification Penetrability (# rows)	9
Burnup	Y
Initial Enrichment	Y
Cooling Time	Y
Pin Diversion Sensitivity[i] (High, Med, Low) in:	
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Independence of (for Fissile Mass Quantification):	
Burnup	Y
Initial Enrichment	Y
Cooling Time	Y
Priority for More Work	2